LESWG Steering Committee meeting (5/16/07) Jacob Bleacher

The ultimate objective is to establish a global network of seismometers on the lunar surface to enable improved modeling of the lunar interior. However, we need to provide a rationale for the initial seismometer in anticipation of not sending or successfully establishing additional hardware. The current rate of impacts on the lunar surface is very poorly constrained. If we are only permitted to send one seismometer due to unforeseen circumstances, the resultant data will not likely provide a substantial improvement to our understanding of the lunar interior, but these data will provide important new insight into the lunar impact rate, which will need to be considered when planning future exploration.

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http://www.nasa.gov/centers/marshall/news/lunar/

http://www.nasa.gov/centers/marshall/news/lunar/program_overview.html

Lunar Impact Monitoring

Mission statement: Use Earth-based observations of the dark portion of the moon to establish the rates and sizes of large meteoroids (greater than 500 grams or 1 pound in mass) striking the lunar surface.

When we observe: Observations are taken between New and 1st Quarter Moon and between Last Quarter and New Moon, when the solar illumination is between 10 and 55 percent. These conditions yield 10-12 observing nights per month.

Who is involved: This project is a joint effort involving NASA's *Meteoroid Environment Office* and the Marshall Space Flight Center's *Space Environments Team*. The participating individuals are:

Richard Altstatt, *Jacobs Technology*
Victoria Coffey, *Space Environments Team*
Bill Cooke, *Meteoroid Environment Office Lead*
Nick Hollon, *Jacobs Technology (Summer 2006)*
Heather McNamara, *Meteoroid Environment Office*
Danielle Moser, *Morgan Research, a Stanley Company*
Leigh Smith, *Space Environments Team*
Rob Suggs, *Space Environments Team Lead*
Ron J. Suggs, *Space Environments Team*
Wesley Swift, *Raytheon*

Observing facility: Observations are conducted at NASA Marshall Space Flight Center in Huntsville, Alabama at the Automated Lunar and Meteor Observatory (ALaMO). The facility consists of two observatory domes, a 15 meter (50 ft) tower with a roll-off roof, and an operations center with laboratory space.

Why it is important: On average, 33 metric tons (73,000 lbs) of meteoroids hit Earth every day, the vast majority of which harmlessly *ablates* ("burns up") high in the atmosphere, never making it to the ground. The moon, however, has no atmosphere, so meteoroids have nothing to stop them from striking the surface. The slowest of these rocks travels at 20 km/sec (4500 mph); the fastest travels at over 72 km/sec (160,000 mph). At such speeds even a small meteoroid has incredible energy -- one with a mass of only 5 kg (10 lbs) can excavate a crater over 9 meters (30 ft) across, hurling 75 metric tons (165,000 lbs) of lunar soil and rock on ballistic trajectories above the lunar surface.

Current meteoroid models indicate that the moon is struck by a meteoroid with a mass greater than 1 kg (2 lbs) over 260 times per year. This number is very uncertain, however, as observations for objects in this mass range are embarrassingly few -- a single fireball survey conducted by Canadian researchers from 1971 to 1985. Factors of several, higher or lower, are easily possible. Indeed recent lunar observations by a Spanish team seem to indicate that the rate of impacts is about two times higher. This too is quite uncertain, being based on observations of only 3 impacts. Clearly more observations are needed if we are to establish the rate of large meteoroids impacting the moon.

But why should we care? The answer is simple: the Vision for Space Exploration eventually calls for extended astronaut stays on the lunar surface. Unlike during the Apollo Program, when the astronauts were on the moon for just a couple of days, astronauts of the next decade will live and work on the moon for up to several months. Spacecraft, vehicles, habitats, and EVA suits must all be designed to withstand the stresses posed by the harsh lunar environment over this period of time. Meteoroids, and the ejecta produced when they create impact craters, are part of this environment. We must characterize this environment well enough for effective designs to be developed. This not only applies to manned activities of the *next* decade, but also to the robotic exploration missions planned for the remaining years of *this* decade. They too must be well-engineered so that they may complete their missions with success. Knowledge of the environment is of major importance.

Meteor showers: Models show 260 large background (*sporadic*) meteoroids per month hitting the moon, which represent only a part of the meteoroid environment surrounding our nearest neighbor. A second part, produced by meteor *showers*, is also present to varying degrees at certain times of the year. It is well known that the Earth experiences meteor showers when it encounters the debris left behind by comets; so too does the moon, though perhaps at not exactly the same time. On Earth these showers are capable of producing spectacular celestial fireworks displays, delighting the public. On the airless moon, however, these showers are swarms of high energy projectiles, producing fireworks only when they strike the surface with tremendous force. During such times, the rate of shower meteoroids can greatly exceed that of the sporadic background rate and may pose a hazard to equipment and personnel on the lunar surface. Looking for meteor shower impacts on the moon at about the same time as they occur here on Earth will yield important data that can be fed into meteor shower forecasting models, which can then be used to predict times of greater meteoroid hazard on the moon.

Observing lunar impacts: Looking for impacts on the moon is as simple as pointing a telescope at its dark portion. When a meteoroid strikes the moon, a large portion of the impact energy goes into heat and producing a crater; however, a small fraction goes into generating visible light, which results in a brilliant flash at the point of impact. This can be seen from Earth if the incoming meteoroid has enough kinetic energy. Just how much is "enough" depends on the equipment used in the observations.

In designing a system to look for these impact flashes, we need to take into account two important considerations. First, we want to see as faint as possible, and secondly we want to see as much of the lunar dark side as we can. The first is important because faint flashes are generally produced by smaller meteoroids, and the smaller the meteoroid, the more there are of them. More meteoroids mean more flashes and hence better statistics on which to base improved models. We can also get more flashes by monitoring as much of the lunar surface as possible, as the number of observed hits is going to be directly proportional to the amount of area seen by our instrument. That's why the second point is important. It turns out that a modestly-wide field optical system (one with a fast focal ratio) meets both of these criteria nicely. At the start of our observing program, one of the instruments we used was a 10" Newtonian reflecting telescope; it had good, fast optics (f/4.7) and enabled us to cover about one sixth of the visible moon (one third of the dark side). The second instrument was a 14" Ritchey-Chrétien telescope with a focal reducer; it has a similar field of view as that of the 10" telescope. The 10" was replaced by a 14" Ritchey-Chrétien telescope in early September. So we perform simultaneous observations of the moon with two identical 14" telescopes.

While you can look for impact flashes with just the telescope and your eyes, it is much better to have a record of the event that can be subjected to detailed analysis. A still camera is not a good choice, as you don't know when the impact will occur. Impact flashes are short, usually less than a half-second, and you would be very lucky to press the shutter button in time to get a picture. Even if you did, you would miss the brightest part of the event, which occurs near the very beginning of the flash. A better choice is a low light level video camera, which records continuously at rates of 1/30th of a second. Hours of this data can be stored on a video tape or computer hard disk for later analysis.

And that is exactly what we do -- we attach an ASTROVID StellaCam EX camera to each of our telescopes, and route the camera output into a Sony tape deck, which converts the video signal into a digital format that is stored on a hard disk. After an observing session, we look for flashes in the data. Our first impact was found by someone simply looking through a couple of hours of video. This can be quite tedious, however, and tired humans can easily miss a short impact flash, so custom computer software was developed to look for the flashes. If one is found, additional software is then used to extract detailed information on the flash -- its brightness as a function of time (light curve), where it was seen on the moon, if it was due to a meteor shower, and so forth. Using this information, we can estimate the mass or size of the meteoroid. If it is a sporadic meteoroid, all we can do is put limits on the size, as its speed can range from 20 km/sec (2 miles/sec) all the way up to 70 km/sec (44 miles/sec). If it is a shower meteoroid, then things are better because every member of a meteor shower moves with the same, known speed. This allows us to calculate a single, less uncertain size estimate.

The above paragraph gives a greatly simplified summary of the analysis. In practice, it is much more detailed, as a flash on the video may be caused by something other than a meteoroid striking the moon. Most of the flashes we see last for only a single video frame (1/30th of a second) and are due to cosmic rays striking the camera's CCD chip. If we had only one telescope we would discount any flash that is only one frame in duration, blaming a cosmic ray as the culprit. However, in doing so, we would probably miss some of the smaller impact events. A better way of eliminating cosmic rays is to use two telescopes of similar characteristics, observing at the same time -- this is what we do. A given cosmic ray can only strike one camera; therefore any flash observed simultaneously with both instruments cannot be a cosmic ray.

There are other possible causes of flashes, such as reflections or *glints* from satellites that happen to move between our observatory and the moon, or *point meteors*, which are meteors in Earth's atmosphere that are coming straight at the observer. Of course point meteors don't hit, but they produce a flash when they ablate. These flashes can be eliminated by looking at the light curve -- an impact flash has a sharp onset, followed by a slower decrease in the amount of light, whereas a point meteor will have a light curve that appears more symmetrical. Flashes produced by satellites can be removed by determining whether or not the flash moves in the video; if it does, then it is caused by a satellite. *Noise* can also masquerade as flashes in the video recording; recording directly to hard drive (instead of recording to videotape and then transferring to hard drive) reduces noise. And using two telescopes to observe simultaneously helps to eliminate this problem.

Part of a comprehensive strategy: Monitoring the moon for impacts is only part of the equation for determining the rate of large meteoroids hitting the moon and the risk they pose to future lunar exploration. In order to get at the size of the impactor, we must figure out how much of its energy is converted into light. This amount, expressed as a fraction of the total energy, is called the *luminous efficiency,* and it depends on the speed of the meteoroid and the nature of the lunar surface where it hits. Current estimates of impact luminous efficiency are little more than guesses, so the *Meteoroid Environment Office* and the *Space Environments Team* have begun a small series of experiments in which lunar surface simulants are struck by small projectiles fired from hypervelocity guns at speeds up to 6 km/sec (13,000 mph). The flashes from these impacts are recorded by a camera like that attached to our telescopes. A comparison of the amount of light energy produced by the flashes to the known kinetic energies of the projectiles will give us direct calculations of the luminous efficiencies. The values can then be applied to our observations and improved meteoroid size or mass values obtained.

Hopefully, a later and more elaborate series of hypervelocity gun experiments will not only enable more luminous efficiency measurements, but also allow for the study of the cratering process in detail. Sizes and trajectories of the ejecta produced by the experimental craters will be recorded and this data used to calibrate sophisticated computer programs called *hydrocodes*. These hydrocodes will then be used to model impacts of large meteoroids on the moon and the resulting ejecta field, in particular how big and how far they travel. These calculations will then form the basis of a realistic assessment of the hazard posed by these cratering events, thought by some to be as great or greater than the risk posed by the meteoroids themselves.

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http://science.nasa.gov/headlines/y2006/28apr_skyisfalling.htm

"Here's what's interesting," says [Bill] Cooke. "Of some 12,000 events recorded by the seismometers, less than half have been explained by known phenomena. There are thousands of tremors caused by ... no one knows what. "He has a hunch: "Many of them may be meteoroid impacts."

"Apollo scientists were very bright," says Cooke, "but they didn't have the benefit of modern computers. We do." Cooke and Diekmann are now loading the old seismic data into machines at the MSFC where they can perform digital calculations at speeds impossible 30 years ago, rapidly trying new algorithms to find previously unrecognized impacts. Critical to the analysis are nine man-made impacts. "NASA deliberately crashed some spacecraft into the Moon while the seismometers were operating," he explains. "They were the empty ascent stages of four lunar modules (Apollo 12, 14, 15 and 17) and the SIV-B stages of five Saturn rockets (Apollo 13, 14, 15, 16 and 17)." Their seismic waveforms tell researchers what an impact should look like.

The truth is, "we really don't know how many meteoroids hit the Moon every day," he says. "Our best estimates come from the 'Standard Meteoroid Model,' which NASA uses to evaluate hazards to the space station and the space shuttle." Problem: The Standard Model is based mainly on Earth-data, e.g., satellite observations of meteoroids hitting Earth's upper atmosphere and human observations of meteors flitting across the night sky. "The Standard Model may not work well for the Moon."

For lunar purposes, "we need more data," says Cooke. Fortunately, there are more data. It comes from Apollo:Clues to how often and how hard the Moon is hit lie in data from four seismometers placed on the Moon by the Apollo 12, 14, 15, and 16 missions during 1969-72. They operated until NASA turned them off in 1977. For years, the seismometers recorded all manner of tremors and jolts, including almost 3000 moonquakes, 1700 meteoroid strikes, and 9 spacecraft deliberately crashed into the Moon. All these data were transmitted to Earth for analysis.